Vacuum 167 (2019) 329–335

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Optimization of strength, ductility and electrical conductivity of a Cu–Cr–Zr alloy by cold rolling and aging treatment

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ARTICLE INFO

Keywords:
Cu-Cr-Zr alloy
Rolling
Twinning
Precipitate
Strength
Electrical conductivity

ABSTRACT

To balance the paradox of both high mechanical properties and electrical conductivity of copper alloys, a nominal hot-rolled Cu-0.4 wt.%Cr-0.3 wt.%Zr alloy strips were subjected to different thermo-mechanical process. The microstructures of the alloys are characterized by optical microscopy and transmission electron microscopy and the mechanical properties and the electrical conductivity are evaluated. The results show that a desired combination of strength, ductility and conductivity can be obtained by controlling the sequence of cold rolling and aging. It suggests that the treatment route with an order of aging followed by cold rolling (ACR) is better than that with the order of cold rolling with aging (CRA). The ultimate tensile strength 568 MPa and electrical conductivity 75.3%IACS are obtained after aging at 450 °C for 3 h followed by 80% cold rolling at room temperature. The high electrical conductivity and ductility is attributed to twin lamellar structure.

1. Introduction

Copper-based alloys which possess admirable conductivity, high strength, excellent fatigue resistance, ease of fabrication are widely used for lots of commercial applications such as railway contact wire, electrode for resistance welding, connectors of various microelectronic devices, and lead frame materials, etc [1–5]. However, the high strength and high electrical conductivity are trade-off for copper and its alloys. To satisfy the growing industrial demands, solid solution, strain hardening and grain refinement are employed [6]. Generally, solute atoms in the copper matrix inevitably worsen the electrical conductivity of alloys [7]. Hence, precipitation strengthened copper alloys via aging treatment are developed to meet an optimized combination of strength and electrical conductivity [8]. The Cu–Cr–Zr alloys, as the representative precipitation strengthened copper alloys, have been used in variety of applications [9].

In recent years, several strategies have been used to improve the strength and electrical conductivity of the Cu–Cr–Zr alloy. Such as, the addition of micro alloy elements and regulation the content of elements [10–14], Ni, Si played a key role on refinement and homogeneous distribution of precipitates in Cu–Cr–Zr alloy, thus increasing the peak hardness and anti-oxidation temperature [10]. The addition of Ce element has been confirmed that increasing the hardness and the electrical conductivity by means of rolling and aging treatment [11]. Producing ultrafine grains due to one-step severe plastic deformation (SPD) and aging, the equal channel angular pressing (ECAP) and high-pressure torsion (HPT) can also refine grains and enhance the strength of Cu–Cr–Zr alloy with the suitable electrical conductivity [15,16]. As well as deformation at ultra-low temperature deformation followed by thermo-mechanical treatment. A desired combination of the tensile strength(690.13 MPa) and electrical conductivity (67%IACS) are achieved by the primary 30% thickness reduction and intermediate aging at 450 °C for 2 h followed by a secondary 60% thickness reduction at the cryogenic temperature [17]. In the recent work, the route with severe rotary swaging and two-step peak-aging treatment was used to obtain a high performance Cu–Cr–Zr alloy with an ultimate tensile strength of 612 MPa, a uniform elongation of 5% and electrical conductivity of 84.7%IACS [18]. It has been found that lots of Cr and Cu_4Zr precipitates have been formed after aging at 450 °C for 1 h, which enhanced the mechanical and electrical properties of the alloy significantly. Therefore, a perfect combination of tensile strength and electrical conductivity were gained for the alloy with 95% reduction at room temperature and aging treatment [1].

It has been reported that Cu–Cr–Zr alloy can achieve excellent mechanical properties and electrical conductivity attributed to the dislocation and precipitation strengthening mechanisms during the rolling and aging treatment [1,5,13,17]. Over the past decades, compared with the equal channel angular pressing (ECAP) and high-

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https://doi.org/10.1016/j.vacuum.2019.06.027
Received 11 May 2019; Received in revised form 20 June 2019; Accepted 23 June 2019

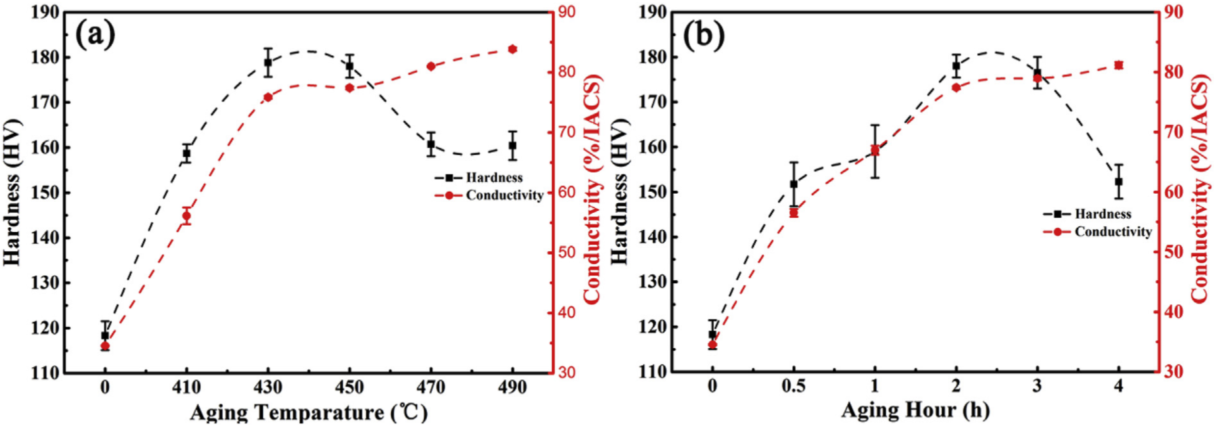

Fig. 1. Hardness and electrical conductivity of Cu-0.4Cr-0.3Zr alloys isochronal aged for 1 h (a) and isothermal aged at 450 °C (b).

pressure torsion (HPT) processing, thermo-mechanical treatment based on rolling and aging is more suitable to be applied in the industrial scale due to the large sample size scales and then it was widely used to obtain the desired synthesis of strength and electrical properties [1,13,17]. However, solution treatment before rolling and aging are included in the previous reported works, which leads to a longer process and higher fabrication cost.

In the present work, a new thermo-mechanical process route is put forward to obtain a balanced combination of high strength, good ductility and high electrical conductivity. It offers a short and cost saving processing by omitting conventional solution treatment, which is considered to be economical and practical for the copper alloys. The evolution of microstructure, including precipitates and dislocations, electrical conductivity, hardness and strength of the Cu–Cr–Zr alloy after the rolling and aging treatment was also studied in detail. It is expected to provide a blue print for exploring high-efficiency process for excellent performance Cu–Cr–Zr alloys.

2. Experimental procedures

The tested material with a nominal composition of Cu-0.4 wt%Cr-0.3 wt%Zr alloy was manufactured by vacuum induction melting under argon atmosphere, and casted in a metal mould. The as-casted billet was then homogenized to improve the homogeneity of the microstructure and then hot rolled to decrease the thickness followed by rapidly quenching into cold water. The hot rolled specimen was polished on both sides, and then divided into small sized specimens for the aging treatment. Then the samples were isochronal aged in an electric resistance furnace at various temperatures in a range of 410–490 °C for 1 h, respectively. Isothermal aging at a selected 450 °C for various holding time was also carried out to confirm the suitable heat treatment parameters. The results show that aging treatment at 450 °C for 3 h is the optimal process for the Cu–Cr–Zr alloy. In order to gain the optimal mechanical properties and electrical conductivity under different conditions, the following processes are carried out.

Process 1 (As-received): the samples are treated by hot-rolling followed by quenched in water without any thermal-mechanical treatment labeled as the As-received samples.
Process 2 (CRA): The As-received samples are firstly cold rolled into 50% reduction of the thickness and then followed by the aging at 450 °C for 3 h, which are labeled as the CR50%A samples.
Process 3 (ACR): The As-received samples are aged at 450 °C for 3 h at first, and then the samples are cold rolled with reductions of 50% and 80%, respectively. The resulted samples are labeled as ACR50% and ACR80%.

Vickers hardness (HV) of samples was measured utilizing a HMV-G 21DT digital tester with a load of 980.7 mN and 10s loading time. The electronic conductivity was measured by a Sigma2008 B/C type digital eddy current metal conductance meter (Xiamen, China). For each specimen, it was calculated at least ten times to get an average value. Dog-bone shaped tensile measuring samples with a rectangular cross-section of 1.5 mm × 2.5 mm and a gauge length of 10 mm were obtained from the bulk sample using the electric spark cutting machine, and were tested utilizing a testing machine (WB-LFM 20 KN) at a strain rate of $1 \times 10^{-3} s^{-1}$. For each case, three experiments were conducted to check the repeatability of the results. Optical microscope specimens were polished and etched in a solution $FeCl_3$, HCl, H_2O, and were observed on Olympus optical microscope equipped with a digital camera. For TEM investigations of the alloy, the discs with 3 mm thickness were sectioned from the parallel plane of the rolling billets, and then mechanically ground and polished down to a thickness of 70 μm. The thin foils were prepared by conventional double-side electro-polishing equipment using a solution of HNO_3: CH_2OH = 3:7 (volume ratio) with the 15 V voltage and at the low temperature −30 °C. TEM observations were carried out by a FEI Tecnai G2 transmission electron microscope operating at 200 KV.

3. Results

3.1. Aging behavior

The variation of hardness and conductivity with aging different temperature and holding time for the as received samples is illustrated in Fig. 1. It can be seen that all samples exhibit significant hardening and distinct increase of conductivity after aging treatment. The hardness (black line with rectangular) and electrical conductivity (red line with circle) of the Cu–Cr–Zr alloy as a function of temperature during isochronal aging for 1 h is shown in Fig. 1a. The micro-hardness increases gradually with the increase of aging temperature and then the over-aging phenomenon results in the decrease of hardness at a higher temperature above 450 °C [11,12,18]. Fig. 1a shows that the peak hardness of ∼179 ± 3 HV is obtained at a temperature range from 430 °C to 450 °C. The value increased by 50.8% compared with the as-received sample one. The precipitations formed as the temperature increases. However, the degree of super-saturation at high temperature is lower than that of low temperature, therefore more solute atoms are dissolved in the alloy and less precipitated from the supersaturated solid solution at high temperature compared to the low temperature [19]. On the contrast, the electrical conductivity increases gradually with the increase of temperature. The electrical conductivity can reach the peak value 83.9 ± 0.3%IACS when aged at 490 °C for 1 h, 154.5% higher than the initial conductivity. The solute particles gradually precipitated from the supersaturated matrix and resulted in the higher conductivity, as the aging temperature increase [1,4]. Based on the results given above, to obtain an acceptable combination of hardness and conductivity, the following isothermal aging at 450 °C is chosen.

Fig. 1b displays the hardness values and corresponding electrical conductivity curves for the alloy isothermal aged at 450 °C. It shows that the hardness of the samples increases rapidly and reaches a maximum value and then decreases with the further increase of aging time. The decrease in hardness of the sample becomes more distinct at aging hour above 3 h. The increased precipitation hardening occurred in the alloys is responsible for the peak value 178 ± 2 HV of hardness, which appears after aging for 2 h [11,12]. While the precipitations grow rapidly with the increased aging time, leading to the gradually decrease of strengthening efficiency [20]. Over-aging begins to take effect owing to further aging time, and thus leading to a sharp decrease in the hardness occurs, so the hardness decreases to 152 ± 4 HV after aging 4 h [11,18]. Meanwhile, the electrical conductivity increases rapidly with the increase of aging time due to the reduced solute atoms in the matrix, and reaches 78.9 ± 0.3%IACS at the peak aging time [11,12,18]. After that the conductivity increases slightly and reaches a stable value. Based on the above results, it can be found that the optimum performance can be obtained with aging at 450 °C for 3 h. In order to improve the mechanical properties further, these aged samples at 450 °C for 3 h were further cold rolled for various deformation strains. For comparison, the effect of sequence of cold rolling and aging treatment on the tensile strength and electrical conductivity were also investigated.

3.2. Mechanical properties and electrical conductivity

The typical tensile engineering stress-strain curves of four samples with different treatments are shown in Fig. 2 and the detailed strength and electrical conductivity values are given in Table 1. For the as-received sample, the ultimate tensile strength (UTS) and yield strength (YS) is 234 ± 5 and 212 ± 8 MPa, respectively. The total elongation is 16.8 ± 1.9% with excellent uniform elongation of 12.5 ± 0.5%. It can be seen that the tensile strength increases significantly after the thermal-mechanical treatments along with a moderate decrease in the elongation to failure. The yield strength values of the sample of CR50%A, ACR50% and ACR80% can reach 377 ± 4 MPa, 485 ± 8 MPa, 545 ± 6 MPa, respectively. Meanwhile, the ultimate tensile strength increases by almost 77.4%, 117.1%, 142.7%, respectively. The values of elongation to failure of the samples decrease from 16.8 ± 1.9% to 12.6 ± 0.4%, 6.8 ± 0.5%, 9.4 ± 0.5%, respectively. It is noted that the uniform elongations decrease significantly from 12.5 ± 0.5% to 1.5 ± 0.2%, 1.5 ± 0.3% for the later two samples, which is supposed to be resulted from the more crystal defects formed during the rolling process. It also shows that the ACR samples behave higher strength than CRA samples. Therefore, the optimum process is aging treatment firstly and then followed by cold rolling deformation. In addition, it is noted that the strength and elongation increase simultaneously with the increase of rolling reduction. After the different treatments, the electrical conductivity of the alloy increases significantly from 34.1 ± 0.5%IACS to 76.7 ± 0.3%IACS, 77.3 ± 0.3% IACS, 75.3 ± 0.2%IACS, respectively. It also proves that a high strength of 568 MPa along with a favorable conductivity of 75.3%IACS is obtained for sample ACR80%.

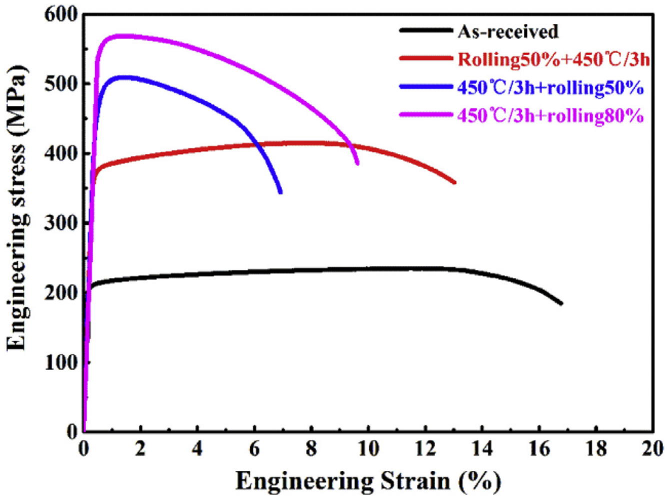

Fig. 2. Typical stress-strain curves of the Cu-0.4Cr-0.3Zr alloy with different treatment conditions.

Table 1
Tensile properties and electrical conductivity of the alloys with various treatment.

Samples	UTS MPa	YS MPa	Uniform elongation%	Total elongation%	Electrical conductivity% IACS
As-received	234 ± 5	212 ± 8	12.5 ± 0.5	16.8 ± 1.9	34.1 ± 0.5
CR50%A	415 ± 3	377 ± 4	8.5 ± 0.2	12.6 ± 0.4	76.7 ± 0.3
ACR50%	508 ± 7	485 ± 8	1.5 ± 0.2	6.8 ± 0.5	77.3 ± 0.3
ACR80%	568 ± 5	545 ± 6	1.5 ± 0.3	9.4 ± 0.5	75.3 ± 0.2

3.3. Microstructure

3.3.1. Effect of aging on microstructure of Cu–Cr–Zr alloy

Fig. 3 shows the microstructures before and after aging treatments of the alloys. As shown in Fig. 3a and b, it can be seen that uniform equiaxed grains with clear grain boundaries before aging play a dominant role in the sample and the average grain size is about 157 μm. In addition, a few twins with some particles mainly can be seen in some coarse grains. After aging treatment, the equiaxed grains grow slightly and the mean grain size is about 193 μm as shown in the histograms inset in Fig. 3b and d and some annealing twins form indicated by the red arrows in Fig. 3c and d. Besides, lots of finer particles are observed both inside the grains and at the boundaries, which are supposed to be formed during the aging process [21].

TEM bright field (BF) images together with the selected area electron diffraction (SAED) patterns of the two alloys before and after aging are exhibited in Fig. 4. As shown in Fig. 4a, it can be seen that a great number of dislocations are densely packed together and form the network structures. At a higher magnification (Fig. 4b), the dislocation tangles and dislocation loops can be seen. In addition, a small amount of precipitated particles exists. Fig. 4c and d shows the microstructure of the aged sample and the grain is much clearer, where a few dislocations can be seen. It is suggested that most of the dislocations have been recovered during the aging process and lots of precipitated particles formed which leads to the increased hardness of the alloy [1,4,12].

3.3.2. Effect of rolling deformation on the microstructure of Cu–Cr–Zr alloy

Fig. 5 shows the microstructures of the Cu–Cr–Zr alloy before and after different rolling procedures at room temperature, it can be seen that the aged sample is dominated by uniform equiaxed grains with clear grain boundaries. After rolling for 50% reduction in thickness at room temperature, the grains are elongated along with the rolling direction as shown in Fig. 5b and c. With the increase of rolling reduction up to 80%, the grain size is reduced drastically and the elongated grains become thinner as shown in Fig. 5d.

Fig. 6 illustrates the typical cross-sectional bright field TEM images and the corresponding SAED patterns of the alloy after aging and cold rolling with different reduction. The average thickness of twin/lamellar structure of the three conditions shown in the column with the blue color is about 299 nm, 128 nm and 76 nm, respectively. As shown in Fig. 6a, it can be seen that the grains after cold rolling are elongated and refined effectively, which is attributed to the rearrangement and

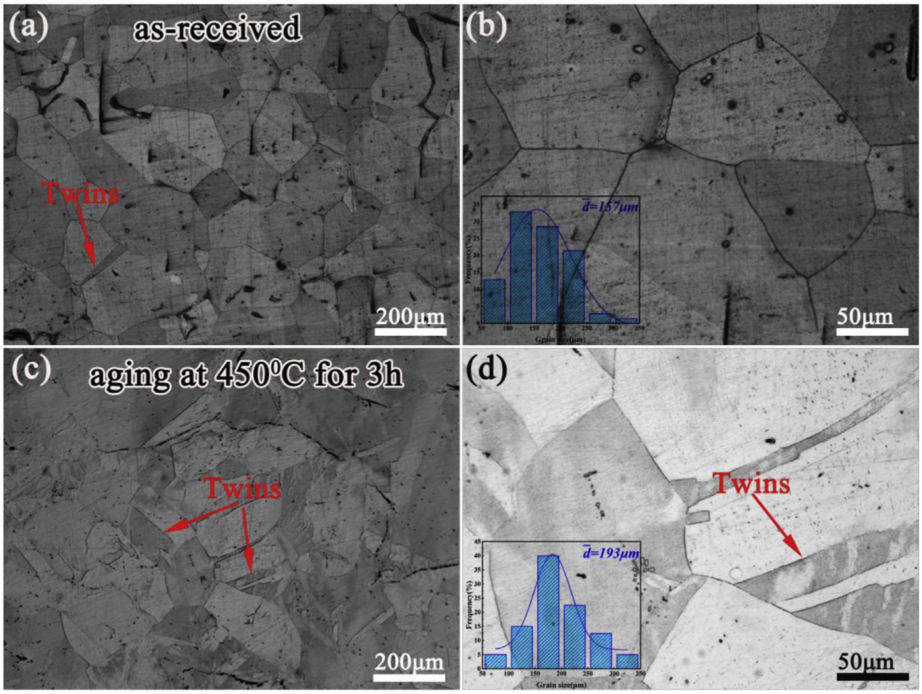

Fig. 3. Optical image of Cu-0.4Cr-0.3Zr alloy under two different conditions with histograms showing the grain size distribution. (a, b) as-received sample; (c, d) aging at 450 °C for 3 h.

evolution of dislocations [1,17]. Meanwhile, annihilation of dislocations also takes place during aging treatment [11,12]. However, there are still a few dislocations tangled together inside the matrix grains. At a higher magnification (Fig. 6b), lots of small sized precipitations can be observed, which are formed during the aging process [27]. It is supposed that the precipitates can be nucleated at plentiful sites which are provided by the dislocations introduced during the rolling process and then the size of precipitates is much smaller, which in turn pin the motion of dislocations and lead to a stronger hardening [15–18]. Fig. 6c and e show the microstructures of the samples ACR 50% and ACR 80%. It can be seen that the microstructure is characterized by a typical lamellar structure and grains are much finer when the cold rolling is carried out after aging treatment, which is consistent with the typical feature of metals deformed at room temperature [22]. In addition, a high density of dislocation cells can be observed in the lamella parallel to rolling direction, and lots of deformation twins formed. Therefore, a significant grain refinement occurred during the rolling process and an ultra fine grain structure formed. It is also noted that high angle grain boundaries (HAGBs) primarily constituted the grains in the UFG structure, but a considerable number of low angle grain boundaries (LAGBs) can also be observed in Fig. 6e [15]. It can be confirmed by the SAED patterns by the inset of Fig. 6e, which show mainly rings with

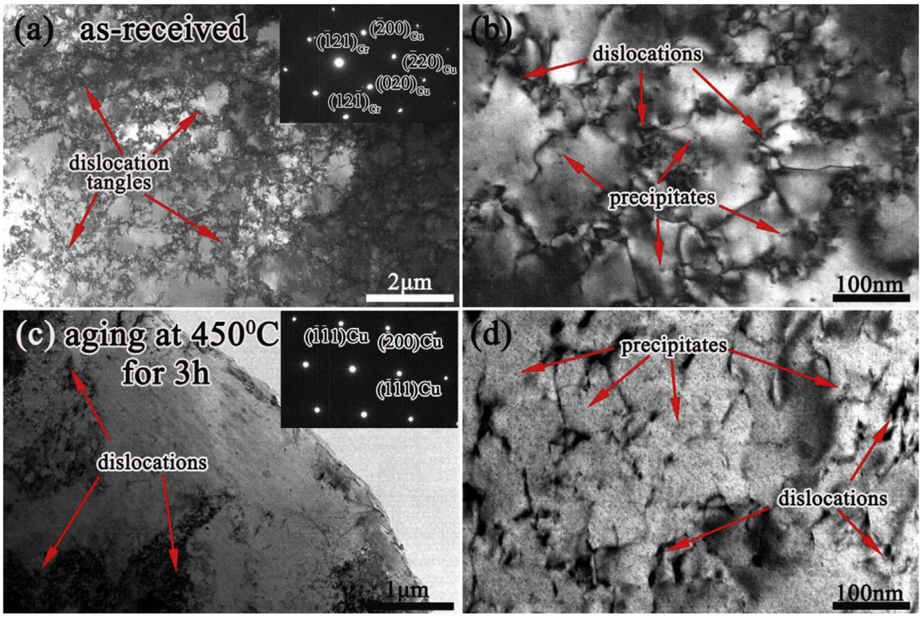

Fig. 4. TEM micrographs and corresponding SAED patterns of Cu–Cr–Zr alloy with the zone axis [001](a) and zone axis [011](b): (a, b) the as-received sample, (c, d) the sample with aging at 450 °C for 3 h specimen.

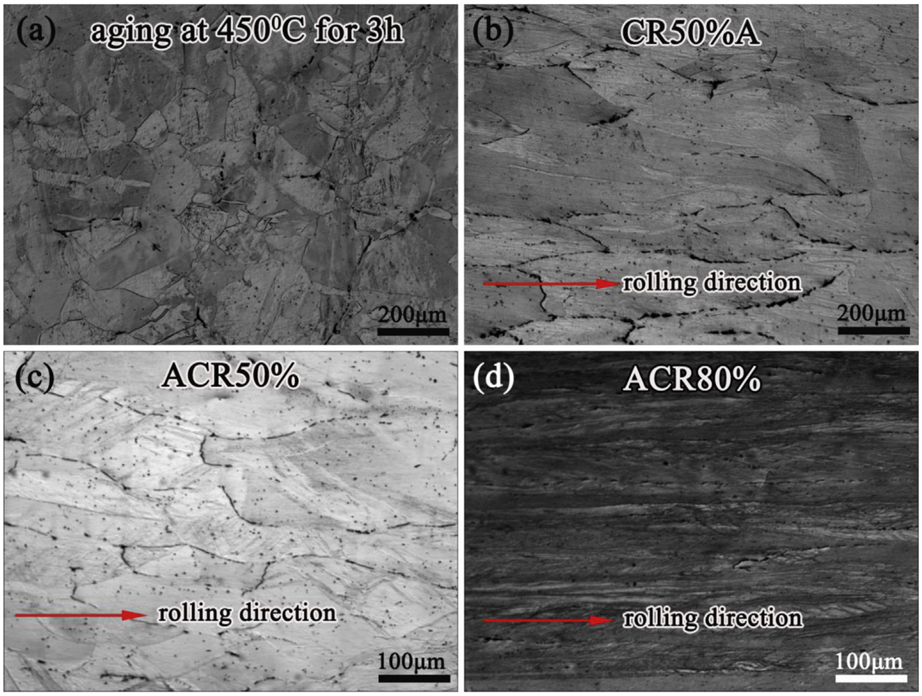

Fig. 5. Optical micrographs of the alloys under different conditions: (a) aging at 450 °C for 3 h; (b) CR50%A; (c) ACR50%; (d) ACR80%.

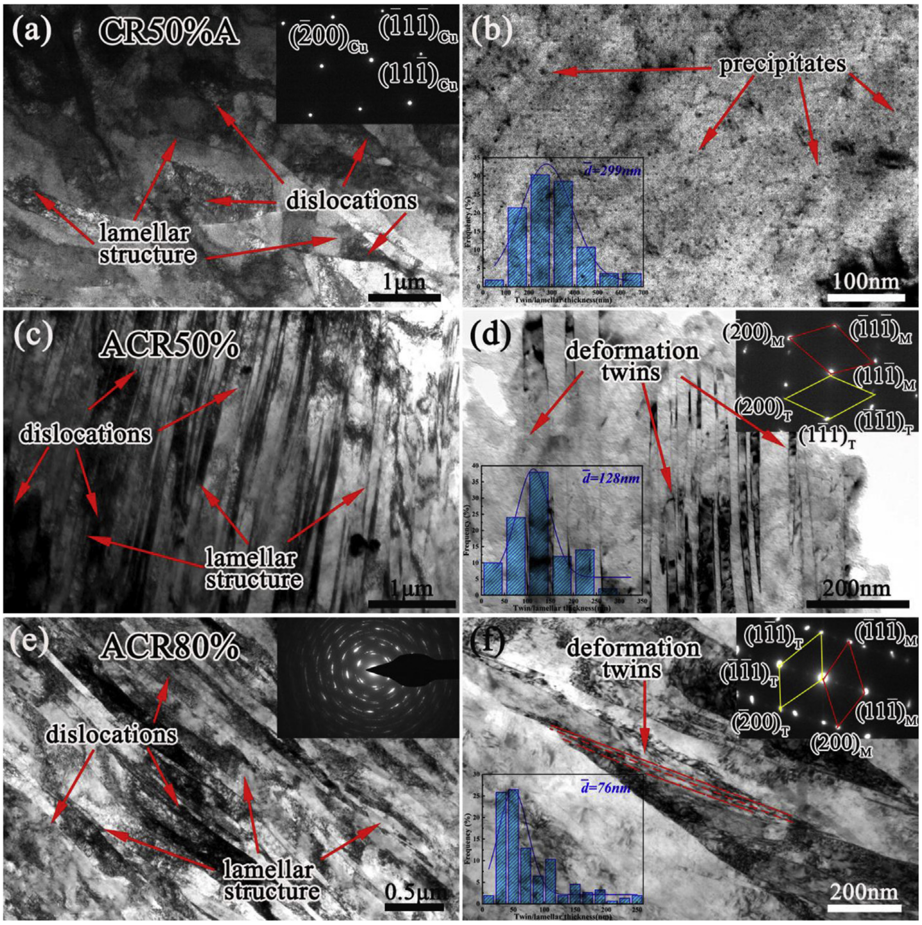

Fig. 6. TEM micrographs and corresponding SAED patterns of the different samples with the zone axis [011]: (a,b) CR50%A; (c,d)ACR50%; (e,f) ACR80%.

diffraction spots pointing out the presence of high amount of HAGBs [23,24]. In addition, there are many deformation twins in the lamellar structure as shown in Fig. 6d and f [17].

4. Discussions

4.1. Effect of aging treatment on hardness and conductivity of Cu–Cr–Zr alloy

It is known that, the microstructure determines the hardness, strength and electrical conductivity of the Cu–Cr–Zr alloys, which is in turn mainly influenced by the processing and heat treatments [1,2]. Cu–Cr–Zr alloys are the typical precipitation-hardened alloys with high strength and high electrical conductivity. The precipitation hardening effect is strongly dependent on the size and volume fraction of the precipitates [25,26].

As mentioned in section 3.1, the alloys can obtain an optimal combination of hardness and conductivity during isochronal aging and isothermal aging process. A distinct hardness increase occurred during aging process for the hot rolled-quenched alloy, which is similar to the aging behavior of ECAP-processed Cu–Cr–Zr alloys reported by Leon [27]. It is pointed out that the onset of recrystallization occurs during annealing of deformed materials at high temperature for a long time. The competition process between precipitation hardening and the dislocation recovery softening is considered to be the main reason [15].The softening is induced by the reduction of dislocations either within the sub-grains or at the grain boundaries just like as shown in Fig. 4. However, the significant hardening of the alloys result from the obviously precipitates increase during aging treatment [11,12,27]. According to Fig. 1, a good combination of hardness and electrical conductivity can be obtained under aging at 450 °C for 3 h. At a lower temperature, the precipitation is insufficient, which leads to a lower value both the hardness and conductivity. When the aging temperature is too high, the precipitates will grow to a larger size, which decreases the hardening effect [12]. Meanwhile, the hardness also decreases due to the larger extent of recovery taken place in the alloy with the aging time increases beyond 3 h [21]. However, the conductivity increases gradually with the increase of aging temperature and aging time, and the scattering of lattice distortion to electrons induced by the dislocations and solute atoms is reduced [8,9].

4.2. Effect of rolling deformation on mechanical properties of Cu–Cr–Zr alloy

Cold deformation is often used in the thermal-mechanical treatments to further improve the mechanical properties of the precipitation-hardened alloys [1,15,18,28]. Furthermore, the sequence of cold rolling and aging treatment on the mechanical properties of Cu–Cr–Zr are investigated for the CRA sample and ACR sample. As shown in Fig. 5, the grains were elongated and refined significantly after cold rolling. Meanwhile, a large number of dislocations and sub-grains were also formed [22]. The yield strength contribution from the grain boundaries (σ_g) can be calculated using the Hall-Petch equation (Eq. (1) [29]):

$$\Delta\sigma_g = \sigma_0 + kd^{-1/2} \tag{1}$$

Where d is the mean grain size, σ_0 is the yield strength of a single grain, and k is the Hall-Petch constant in MPa $m^{1/2}$. Therefore, the strength increased with the decrease of the grain size and the strength of the alloy increase by 142.7% significantly compared with the as-received one [29]. The main purpose of our present work is to study the effect of cold rolling and aging sequence on the tensile strength and electrical conductivity, the same aging temperature and holding time as the as-cast sample were selected for the CR50%A samples and ACR50% samples. Nevertheless, it is not the optimum aging parameters for the cold rolled samples. It has been reported that the aging treatment is usually affected by the pre-deformation, especially the severe plastic deformation before aging [15,16,18]. It shows that the severe deformed samples before aging treatment can approach to a peak hardness value in a shorter hold time and at a lower aging temperature range. Therefore, the optimum aging parameters for the cold rolled samples should be less than 3 h at a given temperature 450 °C. However, we chose aging at 450 °C for 3 h at the over-aging region in order to obtain the admirable combination of hardness and electrical conductivity. In fact, all the samples are at the over-aging state regardless of the sequence of cold rolling and aging, but the degree of over-aging for the ACR50% samples is lower than the CR50%A samples. It is considered that dislocation recovery softening and the reduction of substructure occurred during the aging after rolling, and the grain size of CR50%A samples is larger than the ACR50%. Thus, it is noted that the strength of ACR50% sample is higher than strength of CR50%A sample as shown in Fig. 2.

Generally, the increased rolling reduction results in the enhancement of tensile strength and the reduction of elongation. However, it is noted that the strength and elongation of the samples increase simultaneously as shown in Fig. 2 after 80% rolling reduction. It is noted that the lamellar thickness of ACR80% sample decreases apparently compared with the ACR50% sample, which is corresponding to the SAED patterns. As is known that, twin/matrix lamellar thickness, with the exception of the volume fraction of twins, is a crucial structure parameter for the twinned materials, which plays a crucial role on the mechanical properties [17]. Specially, a high density of nano-scale twins can lead to an extremely high strength, which has been obtained in polycrystalline Cu [30]. In the ACR80% sample, the twin/matrix lamellar thickness decrease distinctly and many nano-scale deformation twins also form, which can effectively improve the tensile strength and ductility [17]. The twin boundaries have a similar strengthening mechanism to grain boundaries, the increased yield strength attribute to Twin boundaries ($\Delta\sigma_{TB}$) can be expressed by a Hall-Petch-type relationship(Eq. (2) [31]):

$$\Delta\sigma_{TB} = \mathrm{K}^{TB}\lambda_{TB}^{1/2} \tag{2}$$

Where K^{TB} is a constant, and $\lambda_{TB}$is the average twin thickness. The average twin/matrix lamellar of the ACR50% and ACR80% sample obeys the following relationship: $\lambda_{ACR50\%} > \lambda_{\mathrm{ACR80\%}}$. Therefore, it can be concluded that $\Delta\sigma_{ACR80\%} > \Delta\sigma_{ACR50\%}$, which is consistent with the tensile curves in Fig. 2. The improved dislocation storage capacity can contribute to the increased ductility and high rate of strain hardening attributed to the formation of abundant twins and stack faults [32,33].

Furthermore, the conductivity for the three samples is comparable to each other and increased to 76.7 ± 0.3%IACS, 77.3 ± 0.3%IACS, 75.3 ± 0.2%IACS, respectively. It is reported that the solute atoms serve as impurity centers in the copper matrix leading to the scattering of electron motions and thus reduce the electrical conductivity significantly [8,9]. However, it is noted that the ACR50% sample has a higher electrical conductivity than that of CR50%A sample, which indicates that deformed structure including dislocations has little influence on the electrical conductivity. Therefore, ACR80% sample with a higher rolling reduction of 80% behaves a higher tensile strength and ductility, along with a comparable electrical conductivity. Based on the above results, it can be concluded that a novel process to optimize the combination of the Cu–Cr–Zr alloys suitable for large scale production with the advantage of short process and low cost is: homogenization → hot rolling followed by quenching → aging at 450 °C for 3 h → cold rolling for 80% reduction. A schematic diagram is proposed as shown in Fig. 7. The high strength of the Cu–Cr–Zr alloys can be attributed to the precipitation strengthening, grain boundary strengthening, and twin boundary strengthening during aging and rolling deformation [17]. Meanwhile, the precipitation and twin lamella lead to the enhanced admirable electrical conductivity.

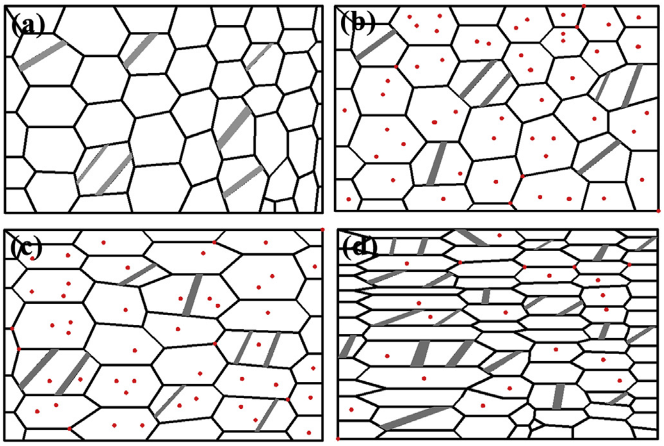

Fig. 7. Schematic diagrams showing the strengthening mechanisms under different conditions: (a) as-received sample; (b) sample aged at 450 °C for 3 h; (c) CR50%A sample; (d) ACR80% sample.

5. Conclusions

The optimization of the mechanical and electrical properties of a nominal Cu-0.4 wt.%Cr-0.3 wt.%Zr alloy was investigated by different thermo-mechanical processing routes in the present work. Based on the results mentioned above, the following conclusions can be obtained:

1. A simple thermo-mechanical process is proposed to obtain a good combination of strength and conductivity for the Cu-0.4 wt.%Cr-0.3 wt.%Zr alloy, a ultimate tensile strength of 568 MPa with a reasonable ductility, and electrical conductivity of 75.3%IACS is obtained after aging at 450 °C for 3 h and the following 80% cold rolling.
2. With the increase of rolling reduction, the strength and ductility can be simultaneously increased, without distinct decrease of electrical conductivity.
3. The grain size and the thickness of the lamellae structure can be refined significantly during the cold deformation, which can increase the capacity of storage dislocation and electrical conductivity.

Acknowledgements

This work is supported by the National Key R&D Program of China (No. 2017YFA0204403) and the Natural Science Foundation of China (Nos. 51731007 and 51501092 and 2012CB932203). The authors also want to acknowledge the support of the Jiangsu Key Laboratory of Advanced Micro-Nano Materials and Technology. The TEM experiments are performed at the Materials Characterization and Research Center of Nanjing University of Science and Technology.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.vacuum.2019.06.027.

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